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THE DEVELOPMENT OF AN AUTOMATED CORRECTION PROCEDURE FOR DIGITAL PHOTOGRAMMETRY FOR THE STUDY OF WIDE, SHALLOW, GRAVEL-BED RIVERS

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ABSTRACT

This paper develops an automated correction procedure for dealing with point errors associated with through-water photogrammetry, for application in the study of clear-water, shallow gravel-bed rivers. The procedure involves combining digital photogrammetry and image analysis techniques to: (i) correct for the effects of refraction at an air–water interface; and (ii) eliminate and reinterpolate points where the bed has not been 'seen'. The correction procedure was applied to raw digital elevation models (DEMs) generated using digital photogrammetry from 1:3000 scale aerial photography of a small reach of the North Ashburton River, New Zealand. The accuracy of corrected and uncorrected DEMs is evaluated using an independent data set. A measure of 'geomorphological usefulness' as well as DEM external reliability is obtained from calculations of water depth distributions and mean bed level. Results show that digital photogrammetry, used in conjunction with image analysis techniques, can successfully be used for extracting high-resolution DEMs of gravel river beds. In exposed areas, errors are small and random, tending to cancel out over large numbers of points. Where water is shallow, and following correction, point elevation errors are statistically no different from those for exposed zones. In deeper water, despite an improvement following application of the correction procedure, elevation errors scale with water depth. The geomorphological potential of photogrammetric survey of large, gravel river beds is demonstrated by the ease and accuracy of calculations of water depth distribution (important for the assessment of a river's ecological and recreational characteristics) and mean bed level (important for the calculation of reach-scale sediment volumes). Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: DEM quality; correction procedure; image analysis; digital photogrammetry; submerged zones

INTRODUCTION

There is increasing interest in fluvial geomorphology in high resolution monitoring of river bed topography, particularly in dynamic, gravel-bed river channels. Several reasons can be identified for this. First, development of numerical models of dynamic river channels, both automated cellular (e.g. Murray and Paola, 1994; Webb, 1995) and physically based (Lane *et al.*, 1995b), emphasizes the need for detailed, distributed three-dimensional information on channel morphology as input boundary conditions and for validation of predictions. Second, digital elevation models (DEMs) have been shown to be useful as a way of visualizing and manipulating topographic information in fluvial geomorphology (e.g. Lane *et al.*, 1996; Heritage *et al.*,

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1998). Third, there is an increasing recognition of the failings associated with using process-based studies to determine and predict changes in river form and sediment transport rates. This has led to calls for a 'reversal' of the traditional methodology whereby processes are instead inferred from changes in channel morphology (e.g. Goff and Ashmore, 1994; Lane *et al.*, 1995a; Ashmore and Church, 1998). At a more practical level, there is also a need to understand the dynamics of river channels to help inform and advise river management decisions.

Central to a DEM-based approach is the acquisition of high-resolution topographic information. This must be distributed across the full area of interest, be of a quality commensurate with the scale of study, and collected and re-collected sufficiently rapidly for there to be only minimal change during the measurement process. Recent developments have made photogrammetry an increasingly attractive methodology for this purpose (Lane *et al.*, 1994; Chandler, 1999), and digital photogrammetry has been successfully used to derive digital elevation models (DEMs) in fluvial environments (e.g. Pyle *et al.*, 1997; Butler *et al.*, 1998; Lane, 1998; Stojic *et al.*, 1998). In particular, automation of the data collection process allows very rapid and inexpensive DEM acquisition.

However, two problems arise in the use of automated digital photogrammetry for the study of large river channels. First, the spatial scale of wide, braided gravel-bed rivers means that vertical aerial images must be used, unless (and unusually) suitable vantage points exist. The problem with these arises from the low relative relief of such channels as compared with the spatial coverage that is required. This means that the camera platforms must be sufficiently far off the ground to cover the area of interest, but not so far that the resolution of the scanned imagery is insufficient to represent the required scale of topography. The problem of areal coverage can be dealt with by using a 'mosaic' of images, but increasing the number of images increases the computational time and resources needed. If multiple images are used, the key research design issue becomes the trade-off between spatial resolution and the practical number of images of the area of interest. For these reasons, application of digital photogrammetry to wide gravel-bed rivers is an extreme case, and special attention must be given to project design.

Second, a well established weakness of the use of photogrammetry for monitoring river channels is submerged topography (Lane, 1994). For small areas, field surveying of rivers at low discharge is the most expensive solution to this problem (e.g. Lane *et al.*, 1994). The development of photogrammetry to address this problem would reduce the dependence upon field survey, and would allow remote analysis of much larger river reaches. Good progress has been made by using bottom reflectance to obtain maps of water depth in shallow gravel-bed rivers (Gilvear *et al.*, 1998), but this is dependent upon field calibration and does not provide data in a fully three-dimensional co-ordinate system. Progress in this area could be made for situations where the water depths are small and the photogrammetry is 'seeing' the bed, but derived elevations are corrupted by a real/apparent depth effect.

This paper seeks to address these issues by developing digital photogrammetry in order to generate high resolution DEMs for a reach of the braided North Ashburton River, South Island, New Zealand. There are three main aims: (i) to establish the research design necessary to yield high quality information on patterns of erosion and deposition; (ii) to investigate the effects of the presence of water on automated stereo-matching by comparing the quality of representation of 'wet' areas with that of exposed, 'dry' areas; (iii) to develop a fully automated correction procedure to help deal with these effects, based on combining DEM output with image analysis techniques of corresponding orthorectified photographs (ortho-photos); and (iv) to demonstrate the geomorphological utility of the associated results.

BACKGROUND

Photogrammetric studies in fluvial geomorphology have focused on bank erosion or channel change. A recognized problem with both groups of studies is submerged topography. Most methods that overcome this avoid the use of photogrammetry in sub-aqueous zones. Studies of bank erosion have generally used terrestrial photogrammetry, with photographs taken from a raised gantry or platform or from the bank opposite the one being measured (Lawler, 1993). Due to the uncertainty associated with through-water photogrammetry, these studies have focused exclusively on those parts of the bank that are above the water

surface (e.g. Collins and Moon, 1979; Barker *et al.*, 1997; Pyle *et al.*, 1997; Dixon *et al.*, 1998), despite the fact that the focus of erosive activity will usually be below the water surface. By ensuring that photography of the bank is conducted only when water levels are low, this problem is avoided to a certain extent but, assuming the channel does not dry up altogether, some parts of the bank will always be excluded from measurement. A similar approach has been used in studies of channel change, with only the exposed areas being monitored photogrammetrically to determine planform changes in channel pattern through time (e.g. Lewin and Manton, 1975; Lane *et al.*, 1994; Dixon *et al.*., 1998; Heritage *et al.*, 1998). This has included the study of channels that have since become abandoned, so that the entire channel bed is exposed at the time of photography (e.g. Sherstone, 1983). A similar approach, though one only possible in laboratory experiments involving hydraulic models, is to drain the river channel prior to taking photographs (e.g. Stojic *et al.*, 1998). Alternatively, photogrammetric survey has been abandoned altogether in submerged zones, with rapid tacheometric survey of bed elevations combined with the photogrammetric measurements obtained from adjacent exposed areas (e.g. Lane *et al.*, 1995a; Lapointe *et al.*, 1998). By not using photogrammetry to monitor submerged zones, these approaches either limit the cases in which photogrammetry can be used to monitor river channels or, by resorting to conventional survey methods, offset the advantages afforded by photogrammetry, particularly the high spatial sampling density.

Fryer (1983) presents one solution based upon gantry-mounted photography taken from above the water surface, where the water is clear, and involving a model to deal with the effects of refraction. It was found that the x,y co-ordinates could be determined with a standard error of $\pm$ 4 mm (approximately 0·06 per cent of the camera-to-object distance), while z co-ordinates could be obtained to a precision of $\pm$ 14 mm (approximately 0·2 per cent of the camera-to-object distance). In neither case could a significant increase in error be detected for measurements made in deeper water, except for the observation that, as water depth was increased, the underwater control point markers became harder to locate. However, this simple situation will normally be complicated by a number of factors. First, in order for refraction errors to be corrected, the position of the water surface must either be known or modelled mathematically (Kniest, 1990). Second, the effect of refraction will depend on the angle of incidence of light passing into the water (Fryer and Kniest, 1985). This makes the position of the water surface only an approximation, but one that is more acceptable with vertical aerial photography, which can be assumed to be vertical. Third, in order for a refractive correction to be made, the submerged bed must be visible on the photographs used. Whether this is possible will depend on both water depth and water turbidity. Only in shallow and/or low turbidity water will the bed be seen. A fourth complication is the presence of patches of ‘white water’, which will tend to occur quasi-randomly in both space and time in areas of shallow water. In these areas, photography will tend to ‘see’ the water surface rather than the bed. Finally, in most cases the air–water surface will not be planar, complicating the geometry of refraction through the surface (Fryer and Kniest, 1985). The extent of the distortion associated with water surface waves will be determined by their shape and size, but even a light breeze can disturb the water surface to such a degree that the resulting images are grossly distorted (Fryer, 1983). A further problem, specific to photogrammetry, is the reliance on two or more photographs, which introduces the possibility of a time lag between exposures, during which the pattern of white water and waves might change.

The uncertainty introduced into photogrammetric measurements by these factors remains largely untested, and the interaction with traditional aspects of the use of digital photogrammetry is unknown. For example, many stereo-matching systems rely upon the epipolar constraint to determine where the system searches for homologous pixel pairs. The effects of refraction upon the trajectories of rays of light may mean that searches must be conducted over larger spatial areas. Thus, some interaction might be expected between stereo-matching parameters and the presence of submerged topography.

This paper is concerned with developing an automated correction procedure, and assessing its utility for fluvial geomorphology.

METHODOLOGY

The field site chosen for this study is a 430 m long reach of the North Branch of the Ashburton River, South Island, New Zealand, just upstream of Thompsons Track Bridge (Figure 1a). The North Ashburton is a

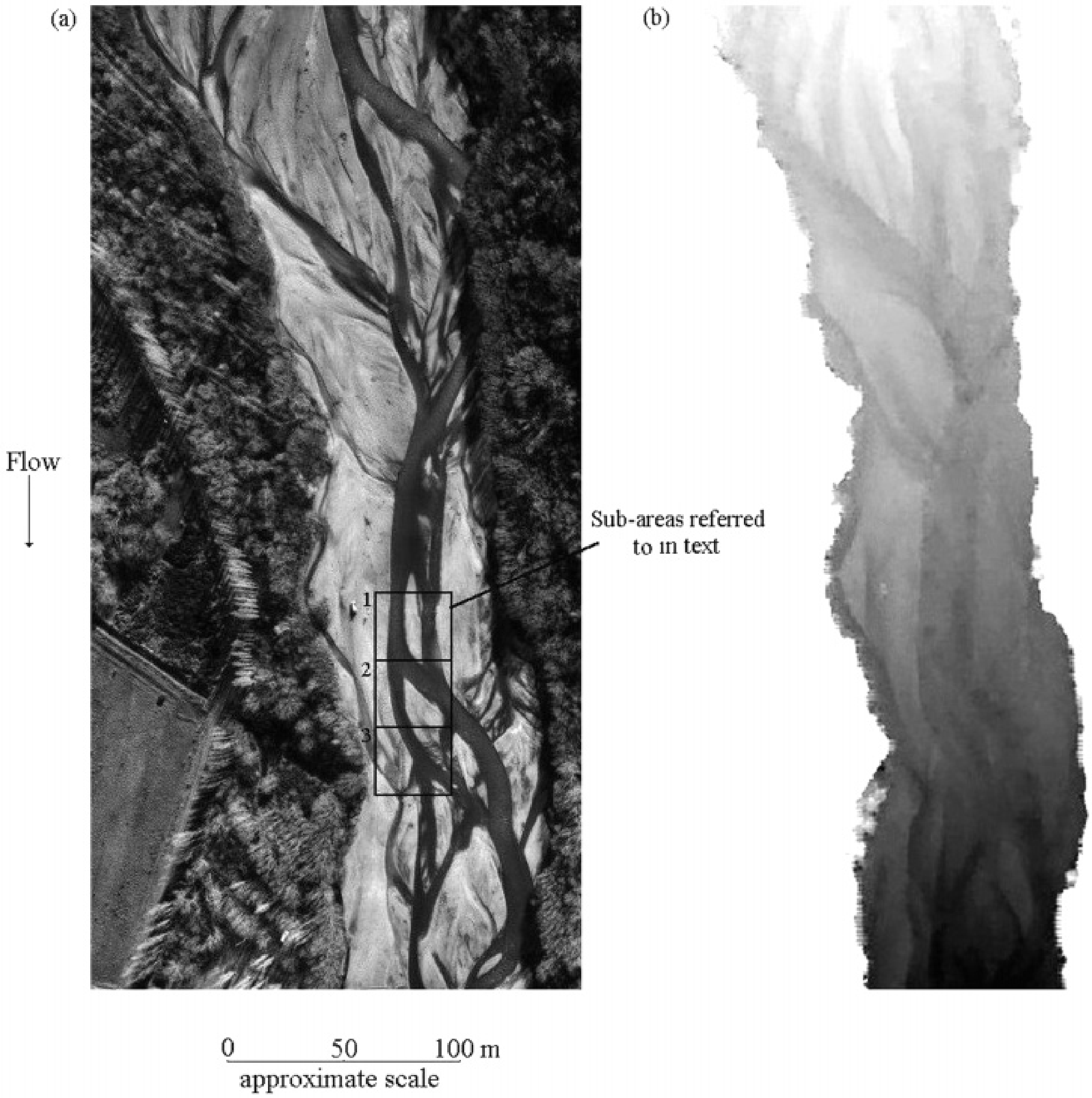

Figure 1. The study reach, The North Ashburton River, New Zealand: (a) the raw imagery; (b) the final corrected DEM for the reach

braided, gravel-bed river that flows eastwards across the Canterbury Plains from the Southern Alps into the Pacific Ocean. The active river bed is approximately 100 m wide at the field site, and is characterized by low vertical relief (1–2 m) relative to the spatial scale. Aggradation has been measured in the reach since 1937, with a wedge of bed material accumulating at an average rate of 5·8 cm per year (Laronne and Duncan, 1992). The braidplain surface is characterized by a mixture of medium to coarse gravels and sand ($D_{84} = 45$ mm) (Willsman, North Ashburton River Survey, NIWA Internal Report, 1995). At normal to low flows, the North Ashburton is a shallow river with low turbidity, meaning that in most areas the bed can be clearly 'seen' on aerial photographs.

The reach was surveyed in May 1995 by the New Zealand National Institute for Water and Atmospheric Research (NIWA) using a Total Station and automatic data logger. Over a two week period, 3500 points were surveyed, of which 1890 (54 per cent) were under water. The sample spacing was 7 m for exposed areas,

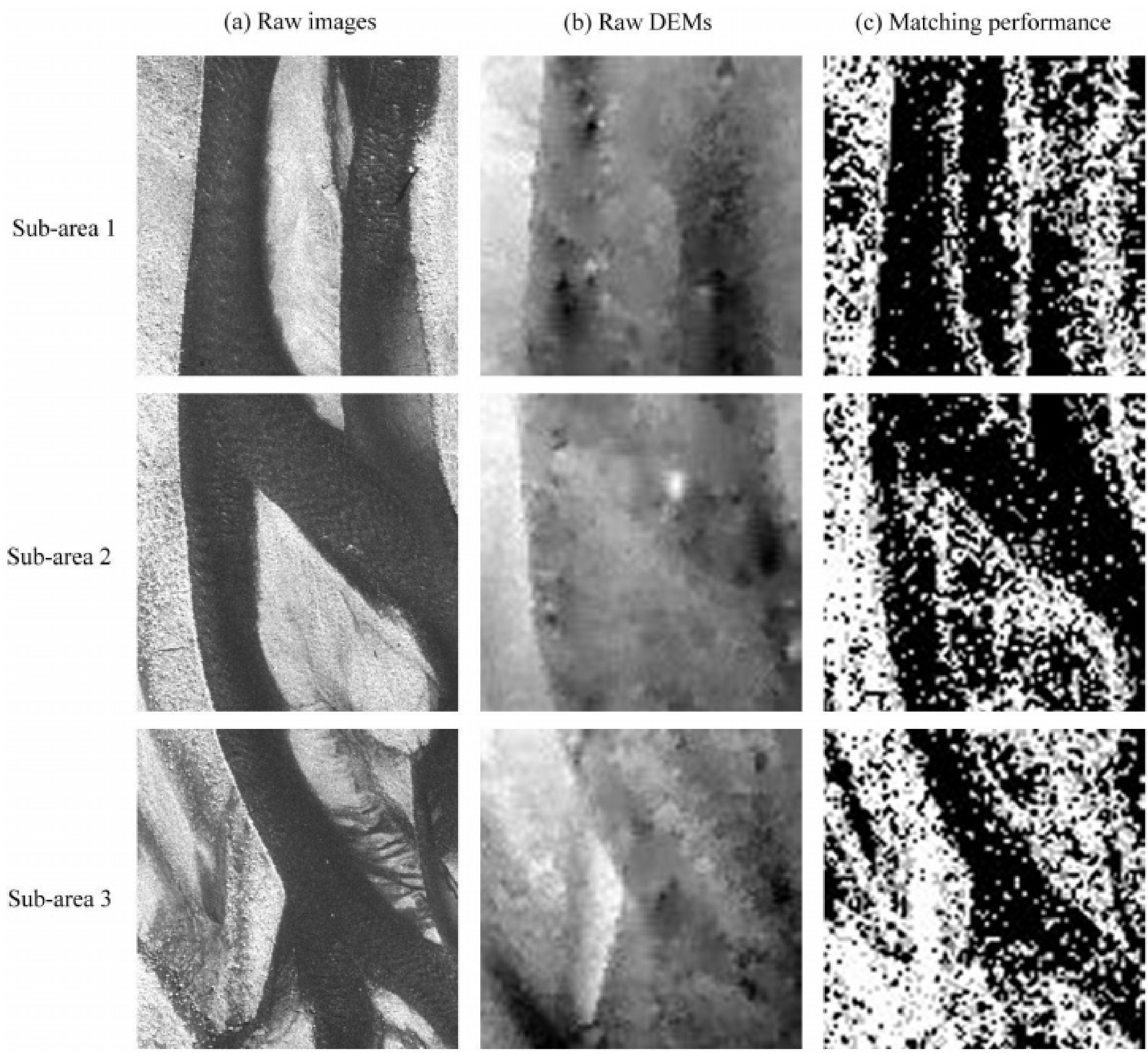

Figure 2. The three sub-areas used for development and testing of the correction procedure. (a) The raw images of the three sub-areas. (b) The raster images of the raw photogrammetrically acquired DEMs, scaled from black (lowest elevations) to white (highest elevations). (c) The stereo-matching statistics files that are produced during DEM collection, which give the spatial distribution of matching performance. White points show good matches, with light and dark grey representing fair and poor matches, respectively. Black points indicate an unsuccessful match and subsequent interpolation

increasing to 2 m in the wetted channels. At each submerged point, water depth was also measured. For the development and testing of the correction procedure, three adjacent 30×30 m sub-areas were selected, in order to reduce computational time during DEM generation (Figure 2a), before the final correction procedure was applied to the whole reach (Figure 1b). The chosen sub-areas contained a high density of ground survey points (388) and exhibited approximately equal areas of submerged and exposed topography. Sub-area 1 is characterized by two distinct channels separated by a central gravel bar. As these channels flow through sub-area 2, the bar is dissected, before both channels are deflected towards the true left bank. Sub-area 3 is more complex, exhibiting a complicated pattern of flow convergence and divergence and a number of developing chutes taking water from the true right-hand channel.

DEM generation using digital photogrammetry was undertaken with a pair of 1:3000 scale photographs taken by Air Logistics (NZ) Ltd using a calibrated Zeiss LMK15 camera at the same time as the ground

survey. The stereo-pair was scanned at 12·5 μm into 256 shade grey-scale using a photogrammetric scanner, giving object space pixel dimensions of 0·038 m. Photo-control was provided by six control targets that were laid out prior to photography. The position of these targets was also measured by Total Station, using the same co-ordinate system as established in the ground survey. Laboratory analysis was performed using the OrthoMAX professional module of ERDAS Imagine software installed on a Sun workstation. The initial stages of digital photogrammetry mirror those associated with conventional photogrammetry, but take place within the OrthoMAX environment. First, camera parameters, basic image data, and the image position and object space co-ordinates of the control points were entered. Second, internal orientation parameters were restored and an absolute orientation using a standard least-squares bundle adjustment was undertaken (Pyle *et al.*, 1997). Automatic stereo-matching then allowed DEM generation using the Vision International stereo-matching algorithm (Butler *et al.*, 1998). This is a hierarchical, area-based correlator (Vision International, 1995), which identifies corresponding points on two images from a search of pixels of similar brightness and contrast based on correlations performed at progressively higher resolutions (Lane *et al.*, 2000). The matching process is controlled by a number of collection parameters, which are defined immediately prior to DEM collection. DEMs were collected for the three sub-areas at a grid spacing of 0·371 m, which was calculated by OrthoMAX to be the highest resolution available given the scale and resolution of the imagery in use and the results from the bundle adjustment. A DEM was also generated for the whole reach at a grid spacing of 1·0 m (Figure 1b). OrthoMAX also allows automated ortho-rectification of photographs, whereby the raw imagery is resampled to remove the effects of terrain variation. Rational functions are used to compute an image pixel co-ordinate associated with a given x,y position and an elevation (z) interpolated from the corresponding DEM based on the 'shape' of the local area (Vision International, 1995).

The study was based upon (i) acquisition of a high quality data set to assess the dry bed points and the wet bed points before and after correction; (ii) development of a data correction procedure for inundated areas; and (iii) assessment of the utility of this approach in terms of geomorphological parameters. The latter is particularly important in demonstrating whether or not the technique can provide geomorphological information that is as useful as compared with conventional approaches.

Development of a correction procedure for submerged topography

In an attempt to develop a method for improving the quality of representation of submerged topography derived using digital photogrammetry, two factors were considered: (i) the apparent increase in bed elevation caused by the refraction of light as it passes through an air–water interface; and (ii) the 'false' matching of points where the photogrammetry does not 'see' the bed. The automated correction procedure presented in this study was developed with the aim of improving the elevation (z) values of submerged points (Figure 3), by integrating the original sub-area DEMs with output from image analysis techniques of corresponding ortho-photos.

First, water surface elevations were estimated by combining the raw DEMs (Figure 2b) with a non-directional edge detection of the original ortho-photo to produce a map of water edge elevations. This was then interpolated to produce a map of water surface elevations. Both kriging and Delaunay triangulation interpolation algorithms were tested, and it was found that kriging gave a visually more realistic water surface. By subtracting the water surface elevation image from the raw DEM, a map of apparent water depth was produced, which was then multiplied by the refractive index for water (1·340) to produce a first order accurate map of 'real' water depth. This was then subtracted from the map of estimated water surface elevation to give a DEM of refraction corrected submerged topography.

Next, points where it was assumed that the photogrammetry had not 'seen' the bed had to be eliminated and interpolated from surrounding points where the bed had been seen. This was based upon the assumption that where a corrected submerged elevation was within a given vertical distance ('elimination value') from the estimated local water surface elevation, yet not near the water edge, the photogrammetry was seeing the water surface. The points that were eliminated in this way were reinterpolated to give the final, corrected submerged bed elevation map, which could be merged with the exposed-bed DEM to produce a corrected DEM of the entire river bed. Both kriging and Delaunay triangulation were considered for this interpolation, and it was found that the triangulation produced consistently better results in terms of both point precision and accuracy.

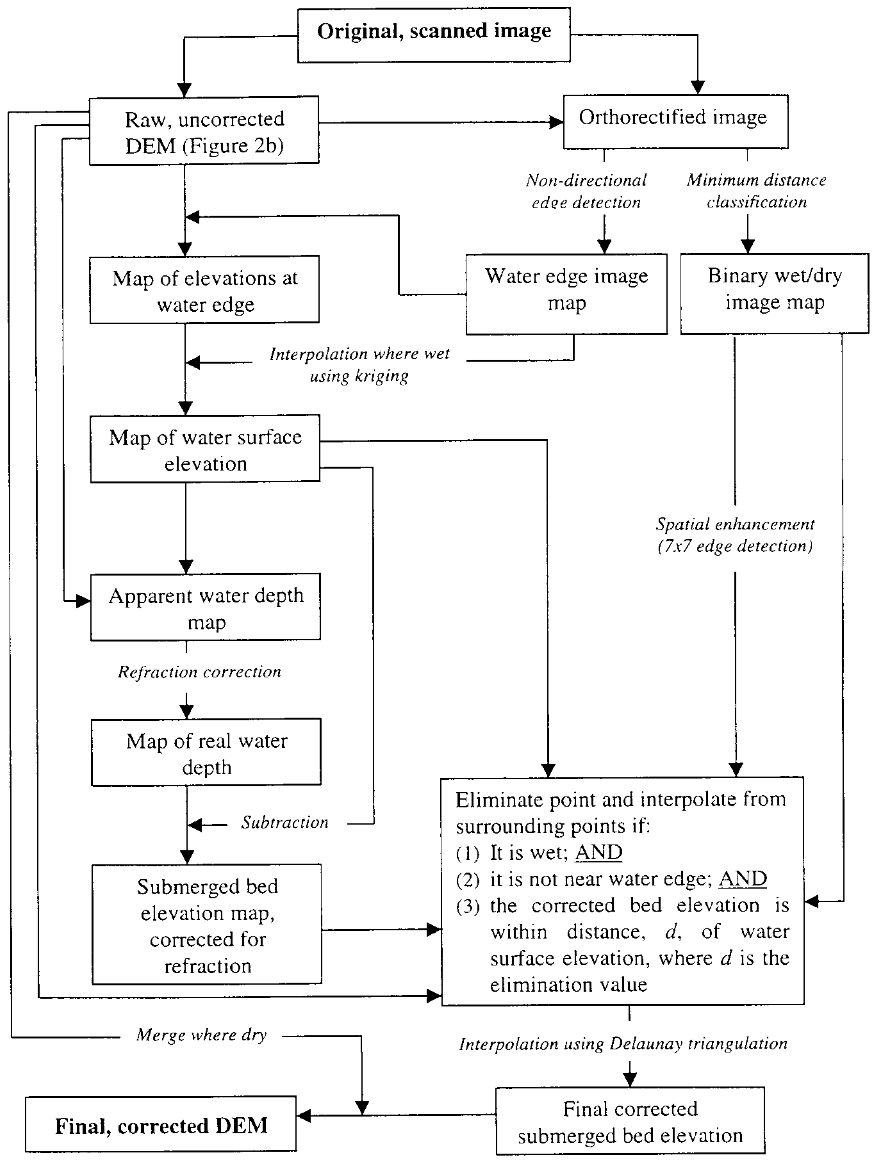

Figure 3. The fully automated DEM correction procedure

Following testing using a number of elimination values, a final value of 0·06 m was chosen. This was felt to be commensurate with the best vertical resolution attainable given the object pixel size (± 0·038 m), the standard deviations of the control points calculated during the bundle adjustment (0·099–0·117 m), and the typical maximum river bed roughness (D_{95} = 64 mm).

Tests of DEM accuracy

The only truly independent means of assessing the accuracy of the DEM generation process is to compare extracted elevations with some independently acquired ground measurements (Torlegå rd *et al.*, 1986). In this study, the ground survey data were used for this purpose, and an algorithm was used to match the location of

each DEM point to the location of the nearest survey point, provided it was within a given search radius. The two identified elevations were then compared. As the search radius is decreased, although the accuracy assessment is likely to be more rigorous, fewer points will be matched. In the sub-areas, a search radius of 0·15m was used, which appeared to give the best balance between accuracy and number of matched points, given the roughness of the floodplain surface and DEM scale and resolution. For the DEM of the whole reach, it was increased to 0·50 m. The quality of DEM representation was assessed in terms of explained variance (R^2), mean error (ME) and standard deviation (SDE), which have been found to be sensitive determinants of DEM quality (e.g. Li, 1992). ME is a measure of accuracy and provides an important indication of any systematic error that is present, while SDE is a measure of precision and provides information on the distribution of residuals either side of the mean value (Lane *et al.*, 2000).

Each of the three indicators of DEM quality (R^2, ME and SDE) were calculated separately for 'wet' (submerged) and 'dry' (exposed) points. In addition, the level of explained variance between surveyed water depth and absolute point error was calculated at each wet point (called D^2 to distinguish it from the R^2 calculated between DEM and survey elevation values). This cannot be used as an indicator of DEM quality *per se*, but acts as an indication of whether the presence and depth of water is a significant influence on the occurrence of point errors between photogrammetrically derived and ground survey elevations. If the presence of water has no effect upon photogrammetrically derived elevation estimates, then it is reasonable to assume that there would be no correlation between water depth and point error. Conversely, if there is a significant relationship, the presence and depth of water might be exerting some influence upon the photogrammetric results obtained.

Tests of DEM external reliability

It is also important to assess the implications of a photogrammetric approach regarding the derivation of geomorphologically useful information, compared to the results obtained using other approaches. This also provides a good test of DEM external reliability, because one of the most effective means of addressing DEM error is to consider its propagation through to derived parameters (e.g. Wise, 1998). Two types of geomorphological parameters can be readily calculated from DEMs: (1) distribution of parameters that characterize the ecological and recreational value of a river; and (2) volumes of sediment storage. In this study, one parameter of each type was examined for the whole reach: (i) the distribution of water depths; and (ii) mean bed level.

The water depth distribution was calculated as a by-product in the correction procedure, so it was a straightforward task to compare it to that obtained from the independent ground survey measurements. The advantages of the photogrammetric approach include the fact that no additional field survey measurements are required, and that the procedure can be fully automated. However, it should be emphasized that following application of this procedure, a 'threshold' depth was noted, above which the bed could not been seen, leading to interpolation from surrounding (shallower) points where the bed was detected. As a result, 'corrected' DEMs still exhibit higher bed elevations in the deepest parts of the channel. Thus, the feasibility of the DEM correction procedure as a whole depends on the water depth distribution at the time of image acquisition.

Sediment storage in a reach can be represented in terms of the mean bed level (MBL) over the reach area. MBL is important, as it provides an indication of aggradation and erosion. Changes in MBL through time allow detection of the passage of sediment waves. Although the residual biases in the wetted areas were expected to be larger than for dry areas, wetted channels only occupy a relatively small proportion of the North Ashburton braidplain. Calculations of MBL and MBL error take this fact into account, and so provide a useful test of DEM accuracy. A photogrammetrically derived high-resolution DEM of the river bed also allows an estimation of the sampling error likely to be associated with traditional surveying methods (e.g. levelling) which typically determine MBL from a few, widely spaced, cross-section surveys. An estimate of the MBL error associated with different cross-section spacings was obtained by extracting cross-sections at a variety of spacings from the DEM, computing MBLs by the end-area method, and then comparing them with the 'ground-truth' MBL obtained from the entire ground survey data set. This was done for both uncorrected and corrected photogrammetrically derived DEMs, as well as for a DEM calculated from the ground survey measurements.

RESULTS

The results are divided into three sections: (i) general DEM quality in terms of matching precision and point accuracy; (ii) assessment of the improvement of the representation of submerged topography obtained by applying the correction procedure; and (iii) evaluation of the derived information.

Uncorrected DEM quality

The original DEMs for the three sub-areas are shown in Figure 2b. Visually, the raw DEMs are encouraging, with river bed features clearly visible, even in the wetted channels, despite the relatively low relief. Figure 2c shows the assessment of stereo-matching performance, with the dark areas indicating that there is a far higher proportion of interpolated (i.e. unsuccessfully matched) points in the wetted channels. These areas can be identified in the raster images (Figure 2b) by 'blurring', for example in the centre of the left-hand channel in sub-area 1. There are also some exposed areas that appear to be heavily interpolated, such as the centre of the mid-channel bar in sub-area 1.

The first indication of the precision of the DEM collection process is given by the distribution of stereo-matched points between quality categories. However, care must be taken when interpreting these statistics, as the values indicate only the confidence that one can have that a particular point has been correctly matched, rather than an absolute measure of precision (Lane *et al.*, 2000). Thus a fair or poor match might be just as precise as a good match, although there is lower probability that this is the case. However, in all three sub-areas, OrthoMAX has been able to match far fewer 'wet' than 'dry' points, leading to a greater proportion of interpolated points in submerged regions. These patterns are statistically significant ($p < 0{\cdot}05$) in terms of the difference between them, so we can be less confident of the precision of submerged terrain representation obtained using digital photogrammetry compared to that of exposed areas. Despite this, there is considerable variation between the sub-areas in the matching performance achieved for wet points. In particular, sub-area 3 shows a greater proportion of good matches and a corresponding reduced proportion of interpolated points, while sub-area 2 has the fewest matched and most interpolated points. It is not clear what is causing this pattern, but it could be linked to differences between corresponding image points on the stereo-photo pair, caused by the slight time lag between exposures. Where differences are greatest, more points would fail to be successfully matched, and consequently interpolated.

In terms of the accuracy assessment parameters, there is excellent representation of exposed DEM areas. For the whole study reach, the ME for 'dry' points is $-0{\cdot}03$ m, with a SDE of 0·122 m. In the three sub-areas, ME ranges from 0·008 to $-0{\cdot}052$ m, and SDE varies from 0·055 to 0·083 m. The more variable ME and smaller SDE of the sub-areas are to be expected, because fewer points are being considered (815 in the whole reach compared to approximately 25 in each sub-area). Nonetheless, they are consistent with the object space pixel resolution of 0·038 m, and suggest that errors are largely random and virtually cancel out with large numbers of points. There is also a significant level of agreement between DEM and surveyed elevations ($p < 0{\cdot}05$) (Figure 4a). The errors associated with wet points (Figure 5a) are significantly higher ($p < 0{\cdot}05$) for all three sub-areas, and the ME and SDE both increase. However, the ME is considerably less than the mean surveyed water depth. It is also significant that the ME has a positive bias in all three sub-areas, indicating the presence of a consistent positive systematic error. There remains a significant level of agreement between DEM and surveyed elevations for all three sub-areas; however, the degree of scatter is noticeably higher (Figure 4b).

There is considerable difference between the quality of wet point representation for each of the sub-areas. Sub-area 3 has the highest DEM quality in terms of each indicator, and this may be linked to the low proportion of interpolated points in the sub-area. However, the relationship between matching precision and submerged surface quality appears to be more complicated than this, with sub-area 1 having by far the lowest quality despite having fewer interpolated points than sub-area 2. The relatively high values of D^2 in sub-areas 1 and 3 suggest a stronger relationship between the error of wet points and depth of water at that point ($p < 0{\cdot}05$) and that the presence of water is a potential cause of point inaccuracies. In sub-area 2, D^2 is much lower but still significant ($p < 0{\cdot}05$).

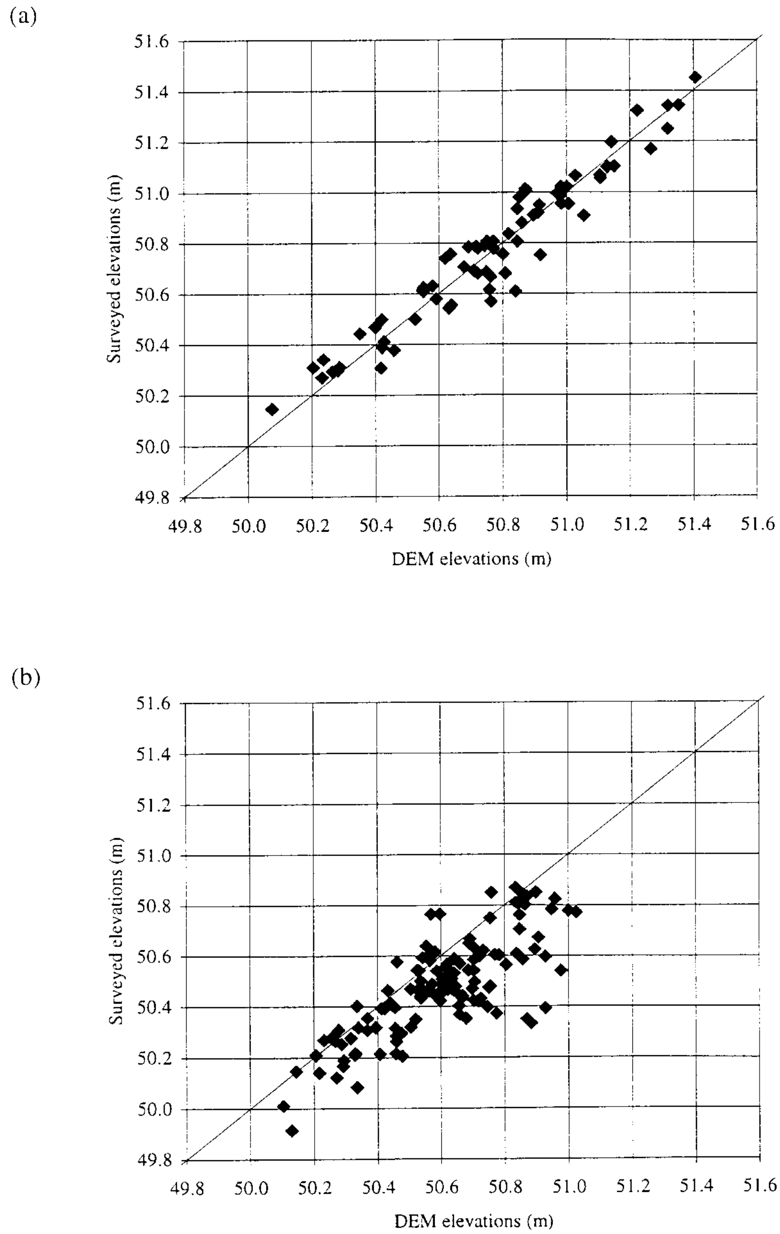

Figure 4. A comparison of elevations obtained from the independent ground survey with those derived using digital photogrammetry for 'dry' (4a) and 'wet' (4b) points for the three sub-areas combined

One possible explanation for the variations in DEM quality for submerged topography between sub-areas is the water depth distribution in each. Figure 6 shows the water depth distributions for each sub-area obtained from the ground survey. Sub-area 3, which exhibits the highest quality of wet points, is a relatively shallow reach, with a mean depth of 0·17 m and no measurements of water deeper than 0·42 m. By contrast, sub-area 1, which has the lowest quality of wet points, has a far wider range of water depths (up to 0·72 m), and a much higher mean depth (0·34 m). Sub-area 2 is somewhere in the middle in terms of both DEM quality and water depths. This suggests that the most important determinant of DEM quality is the range of water depth present.

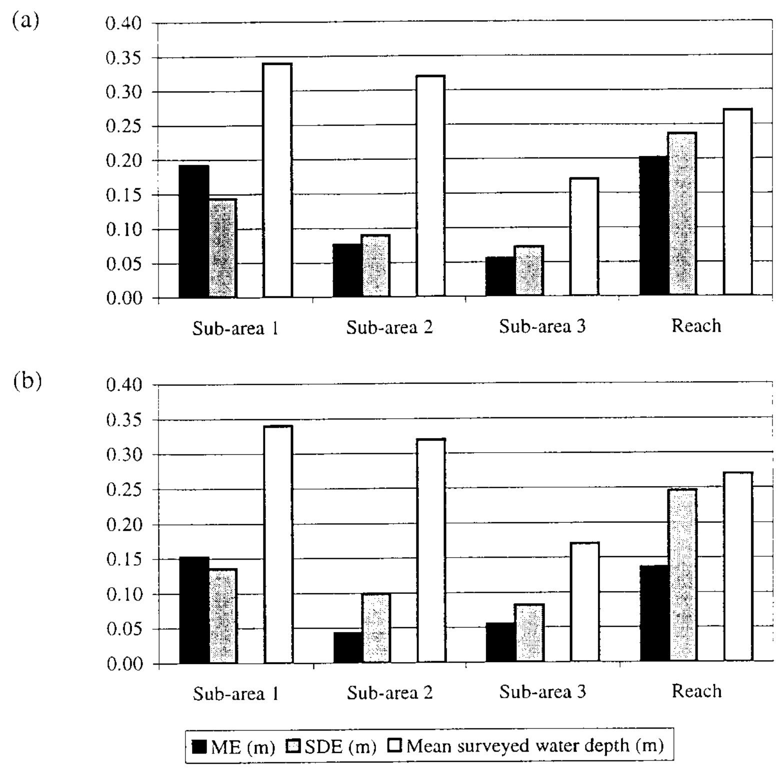

Figure 5. An assessment of the accuracy of 'wet' points (a) before and (b) following correction for each sub-area and the reach as a whole. Measured water depth is also shown

For shallower areas (less than about 0·4 m), it appears that the errors associated with stereomatching submerged points are relatively low. In deeper water, where perhaps the bed can no longer be seen, the errors increase.

Overall, it is clear that the quality of wet points derived using digital photogrammetry is lower than that of dry points, in terms of both precision and accuracy. Apart from the water depth distribution, which is an externally imposed environmental constraint, there are three photogrammetric factors which may contribute to this inaccuracy: (i) the stereo-matching statistics suggest that there is poorer stereo-matching of wet points during DEM collection; (ii) the presence of a positive systematic error with a significant level of association with water depth, which is likely to be due to the apparent 'shortening' of distances caused by refraction through water; and (iii) the variability of ME and SDE between sub-areas corresponds to differences in water depth distribution, suggesting that there may be a maximum depth beyond which the method sees the water surface rather than the bed. Despite the presence of relatively large errors in submerged zones, it is encouraging that these errors, and more importantly their possible sources, can be identified in this way, as this suggests the first steps towards developing the correction algorithm. It is now clear that this algorithm must correct: (i) those point elevations where the bed is seen but refraction matters; and (ii) those points where the water surface is seen rather than the bed. In addition, attention must be given to reducing levels of interpolation where this is due to the effects of refraction upon the matching process through consideration of DEM collection parameters.

Assessment of DEM quality following application of the correction procedure

Figure 5b shows the accuracy assessment parameters after application of the correction algorithm. There is considerable variation in the response of the three sub-areas to the correction procedure. Sub-area 1, with the

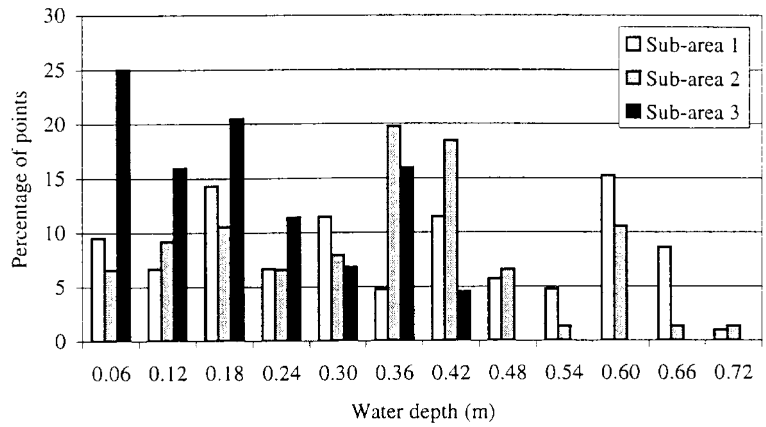

Figure 6. Surveyed water depth distributions for the three sub-areas

lowest initial DEM quality, improves markedly in terms of all three indicators, and shows significant reduction in mean error (and hence the systematic bias) in all three corrected DEMs ($p < 0{\cdot}05$). The improvement in DEM quality in sub-areas 2 and 3 is smaller, although ME decreases in both cases. It is perhaps significant that the initial, uncorrected DEM quality in these two sub-areas was greater than that of sub-area 1.

For the reach as a whole, the correction procedure improves the quality of submerged points in terms of ME, with a statistically significant reduction in point errors when all depths ($p < 0{\cdot}05$). This indicates how the errors associated with submerged points become more random following correction and, despite a slight increase in SDE, are therefore more likely to cancel out with large numbers of points. Nevertheless, following application of the correction procedure, there remains a strong relationship between water depth and point elevation errors (Figure 7). In water less than about 0·4 m deep, ME and SDE reduce to levels similar to exposed areas. For water depths greater than this, despite a consistent reduction in ME by the correction procedure, both ME and SDE are greater than in exposed areas. Another demonstration of the effect of the correction procedure is given by examining the change that occurs at a single cross-section (Figure 8), which clearly shows how the main channel is 'deepened'.

This accuracy assessment for the surface as a whole is based on the response of a small sample of points, and there are obvious problems judging the accuracy, and its improvement, in this way (Lane *et al.*, 2000). There are approximately 4000 wet points with associated pixel elevations within each sub-area DEM. Yet, the data sets used for quality assessment consisted of only those DEM points within 0·15 m of a surveyed elevation, totalling 54 points (or 1·5 per cent of pixels) in sub-area 1, 48 points (1·2 per cent) in sub-area 2, and 23 points (0·55 per cent) in sub-area 3. For the whole reach, the submerged elevation accuracy was assessed using a data set of 700 points, 2·1 per cent of all wet pixels in the reach. It is recognized that the probability that the response of these small samples of points is identical to the response of wet points as a whole is low, representing a general problem with any assessment of DEM surface accuracy. A better indication of DEM quality is obtained by either expanding the check data sets used or by examining a derived parameter.

In this study, two derived parameters are examined: the water depth distribution and MBL calculations. Figure 9 shows the distribution of water depths obtained from the ground surveys, uncorrected DEMs and corrected DEMs for the study reach. It is clear that the water depth distribution calculated from the uncorrected DEMs is much more heavily skewed towards shallower water than the ground survey measurements. Introduction of the correction algorithm for refraction and point elimination results in a reduction in the degree of skewness. The reduction is greater as the elimination value is increased so that more shallow points are interpolated, producing more realistic water depth distributions. A possible

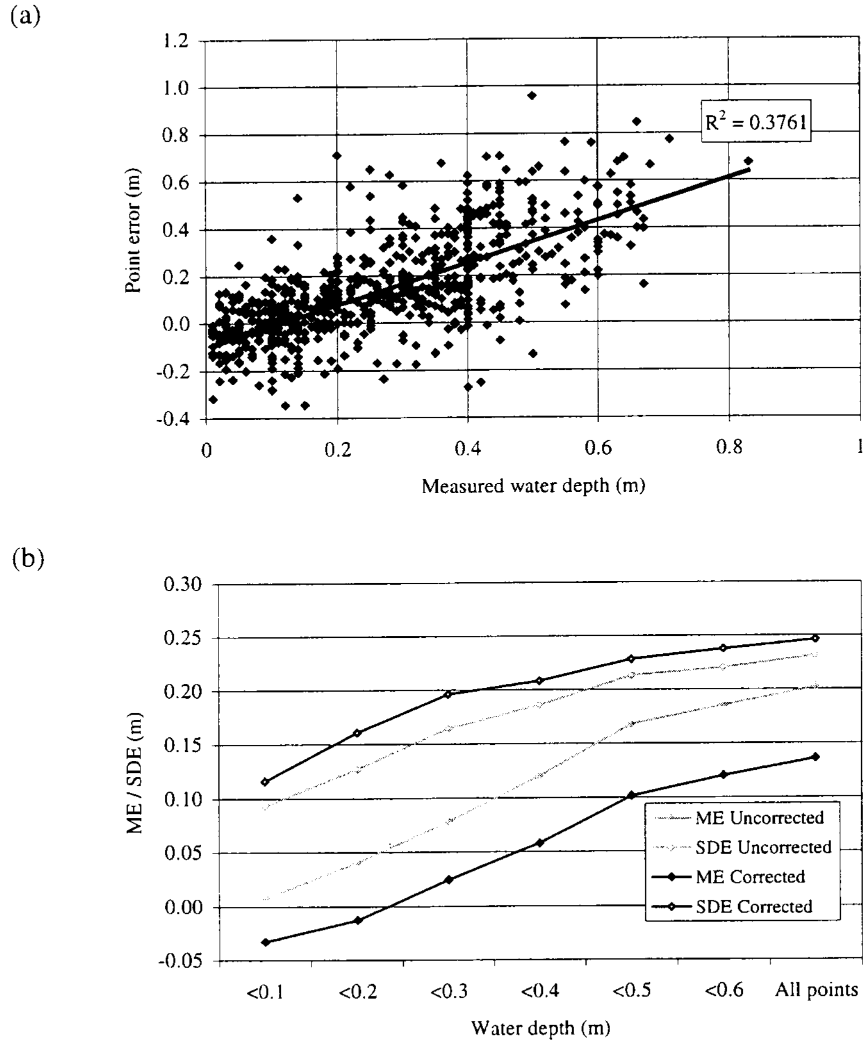

Figure 7. An assessment of the relationship between the submerged point error and water depth for the whole reach. (a) Plot of measured depths against the difference between photogrammetrically derived and measured point elevations for the corrected DEM of the whole reach. (b) Relationship between water depth and ME and SDE before and after correction

explanation for the apparent importance of the elimination value is that just because the photogrammetry does not 'see' the bottom does not necessarily mean that it detects the water surface. It may in fact detect a point further down in the water column, which is why higher elimination values are required. This phenomenon was also reported by Lane *et al.* (2000) with regards to photogrammetric detection of points slightly below the top of a vegetation canopy.

Figure 10a shows the MBL analysis performed for the uncorrected and corrected DEMs. The correction procedure is found to reduce the whole-reach MBL error from about 23 mm to about 2 mm when the whole data set is used in the MBL calculations. To put these figures into context, a MBL error of 1 mm corresponds to a volumetric error of approximately 35 m^3 over the whole reach. It is also useful to compare this level of MBL bias against the error in reach MBL when the reach is represented by only a small number of cross-sections, as with a conventional monitoring programme. Figure 10b shows that MBL error tends to zero as the

Figure 8. An overview of the effect of the correction procedure for an individual cross-section, showing the section (a) before and (b) after correction. The surveyed bed (solid) and water surface (dashed) elevations made along the cross-section are marked in grey

number of sections is increased, as would be expected, but the error only becomes consistently less than the 2 mm bias associated with the corrected photogrammetry when the number of sections is greater than about 10. Thus to match the accuracy of the corrected photogrammetry at defining MBL over the study reach, a ground survey would have to use sections spaced no more than about 45 m apart. The inadequacy of widely spaced cross-sections to represent river bed topography is also highlighted in Table I. This shows how the error in estimated reach sediment volume increases as the spacing between ground surveyed cross-sections is increased. The North Ashburton River is currently monitored using cross-sections spaced approximately 200 m apart, which represents an estimated error in volume of over 100 000 m^3 for the study reach. Table I also demonstrates that, even before correction, photogrammetry produces a data set that has a much lower error in volume associated with it than the current monitoring programme. Following correction this error is reduced further, becoming negligible compared to the magnitude of the sediment volumes involved.

CONCLUSION

These results demonstrate the potential of digital photogrammetry as a geomorphological tool in certain fluvial environments. For exposed areas, photogrammetry gives excellent topographic representation, with a

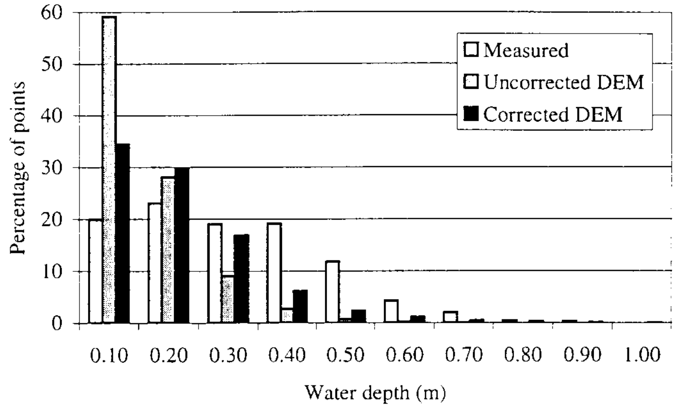

Figure 9. Comparison of the surveyed water depth distributions with those obtained from uncorrected and corrected DEMs for the whole reach

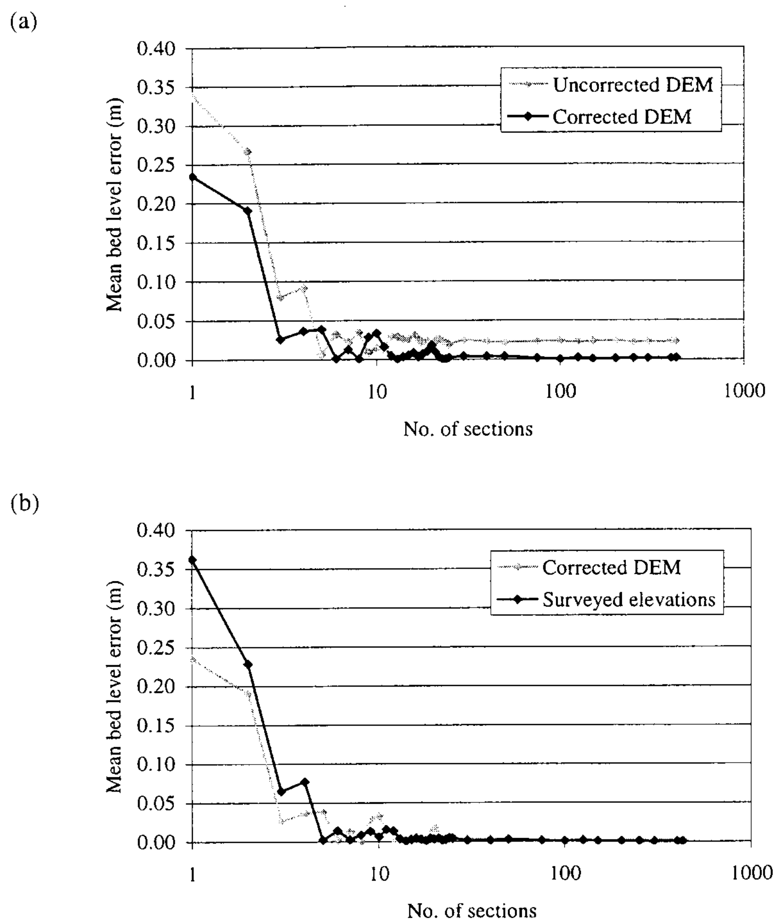

Figure 10. Mean bed level (MBL) analysis for the whole reach. (a) Comparison of MBL error calculated from photogrammetrically derived DEMs before and after correction. (b) Comparison of MBL error calculated from the corrected DEM with the same analysis performed for ground survey measurements

Table I. A comparison of sediment storage volumes obtained from uncorrected and corrected photogrammetry, and from a small number of cross-sections, as with a conventional monitoring programme. Error in volume is determined with respect to the 'ground-truth' volume calculated from the entire ground survey data set

	Data used			
Method	Number of cross-sections	Approximate downstream spacing (m)	Reach volume (m^3) above 0 datum	Error in volume (m^3)
'Ground-truth' ground survey	428*	1*	1708884	–
Photogrammetry, uncorrected	428*	1*	1710679	1795
Photogrammetry, corrected	428*	1*	1709080	196
Ground survey	44	10	1709254	370
Ground survey	18	25	1705665	3219
Ground survey	9	50	1714384	5500
Ground survey	5	100	1687395	21489
Ground survey	3	200	1817605	108721

* Volume calculated using a grid-based data set with a 1 m grid spacing

level of accuracy similar to conventional survey techniques. In wetted areas the errors associated with photogrammetric measurements are greater, but scale with water depth. Below depths of about 0·4 m, the errors associated with photogrammetric measurement of submerged topography following correction are no different from those found in exposed areas. As water depth increases above this, ME and SDE both increase. Consequently, the range of water depths that can be measured photogrammetrically depends on the accuracy required for point elevations.

Also found to be important for the reduction of errors in submerged zones are the DEM collection parameters, set by the user in OrthoMAX prior to DEM generation. For instance, tests have demonstrated that the 'maximum parallax' parameter is particularly important with regard to refraction effects, as it controls the vertical search range considered during automated stereo-matching. Smaller errors in submerged elevations were obtained using a maximum parallax value greater than the default value (i.e. by increasing the vertical search range).

By their nature, braided rivers have distributed and shallow flow, so those with clear water are ideally suited to photogrammetric measurement and monitoring, as demonstrated by the derivation of water depth and MBL for the North Ashburton River. A photogrammetric approach to monitoring rivers such as these produces a huge increase in the spatial density of sampled points, compared to the widely spaced cross-sections used at present to survey braided rivers in many parts of the world. Furthermore, the time required for field data collection is limited to control points only, and therefore significantly reduced, allowing more frequent resurveys. Thus, this method has the potential to revolutionize the monitoring of wide, clear-water, gravel-bed rivers. However, many braided rivers, such as those carrying glacial outwash, are turbid even at normal flow conditions. Subsequent research will investigate how photogrammetric and image analysis techniques can be applied to turbid braided rivers, where the bed is not visible. In these cases, bed elevation can be determined based on image analysis of differences in water colour (e.g. Gilvear *et al.*, 1998).

This research has also shown the potential of combining digital photogrammetric output with image analysis techniques in a way relatively untested in a geomorphological context. One of the major benefits of digital photogrammetry is that the output is in digital form, which allows further data analysis to be carried out very easily. In this study, a correction procedure was developed and applied in an incremental manner; however, the potential exists for the whole process to be executed at once. Full automation of the correction procedure would also allow modifications to be made relatively simply, such as the selective application of the correction procedure. It has been found that shallower areas do not seem to benefit as much from the correction, so it could perhaps only be applied in areas where the mean water depth was known to be greater.

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